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Published in:
Planning Post Carbon Cities: 35th PLEA Conference on Passive and Low Energy Architecture, A Coruña, 1st-3rd September 2020

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Fragkia, V., & Foged, I. W. (2020). Exergy-Based Responsive Building Composites For Thermal Control Stimuli of an Adaptive Envelope . In J. Rodríguez-Álvarez, & J. C. Gonçalves (Eds.), *Planning Post Carbon Cities: 35th PLEA Conference on Passive and Low Energy Architecture, A Coruña, 1st-3rd September 2020: Proceedings* (Vol. 2). University of A Coruña & Asoc..

Exergy-Based Responsive Building Composites

For Thermal Control Stimuli of an Adaptive Envelope

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ABSTRACT: The paper presents and discusses new methods to identify, understand, develop and test novel timber composites for exergy-based adaptive behaviour. The aim of the paper is the development of new design integrated methods for the implementation of active responsive materials in architecture and construction, focused on application for intrinsic thermal responsive and adaptive architectural surfaces. Through material-driven and computational studies, the paper presents a material design survey across three groups of responsive timber composites – single-veneer elements, bi-layers and functionally graded materials (FGM) and a systematic comparative review of their dynamic thermal responsive and structural performance, in relation to operative temperature regulation. Based on the first studies, an oak responsive specimen is developed and further tested towards implementation, as part of an adaptive envelope demonstrator. The research findings suggest that the coordination between geometric arrangement, material layout, hierarchy and binding techniques between the different oak layers leads to the development of a wider range of behavioural system outputs and allow for high resolution steering of the exergy-based responsive timber composites performance in an architectural scale. Finally, the paper speculates on future fabrication strategies and architectural applications of multi-material composites that could introduce new hybrid properties in the responsive architectural system.
KEYWORDS: material studies, timber composites, thermal responsive, building envelopes

1. INTRODUCTION

Building culture is facing an increasing demand for new design and construction strategies that can improve a building's energy efficiency during its erection and life cycle. The necessity for such change is affirmed by global events, such as ecological degradation, resource scarcity and other environmental-related issues [1]. Moreover, the built environment accounts up to 50% of the global CO_2 emission [2,3], when including the construction phase, just as it consumes vast amounts of energy in running mode, through HVAC systems. This challenge incites research into new material practices that allow for low embodied energy, and by focus on exergy-based responsive systems. Predominantly, responsive systems in architecture rely on digitally controlled mechanical systems with high building complexity, unsustainable material components, and high-energy consumption for their consistent operation and maintenance [4]. In contrast to this superimposition of technical equipment, the enquiry discusses new methods to identify, understand, develop and test novel timber composites for exergy [5] based adaptive behaviour, developable into adaptive building envelope. The aim of the paper is the development of new design integrated methods for the implementation of active and responsive materials in architecture and construction, focused on application for intrinsic thermal responsive and adaptive architectural surfaces. Current studies on the development of active-skin systems provide a wide variety of material systems and configurations, varying from hygroscopic performance of single and bi-layer veneer components [6,7] bi-materials combining wood with various isotropic metals and plastic [8] and multi-grain timber composites [9]. However, only few can predict the performance and efficiency of such skin systems [10]. Through material-driven and computational studies, the paper presents a material design survey across three groups of responsive timber composites, single veneer elements, bi-layers and functionally graded materials (FGM). The research employs a systematic comparative review of their dynamic thermal responsive and structural performance, in relation to operative temperature regulation. Equally concerned with design at the scale of material, element and system, an oak responsive specimen is developed and tested as part of an adaptive envelope demonstrator, focusing on the fabrication and assembly methods used for its development. The experimental case study provides a comprehensive overview of the parameters, variables and syntactic elements for the design, fabrication and steering of thermal adaptive exergy-based building composites. Moreover, it discusses their implementation into architectural design, allowing the potential to embed design into active, material-driven, building-scale construction. Finally, by utilizing the thermal responsive capacities of wood veneer as means of material thinking, the paper discusses on future robotic fabrication strategies and advanced design methods for the development of multi-material composites. These could introduce new hybrid properties, allowing for local and global control within one thermally driven responsive architectural system.

2. METHODS

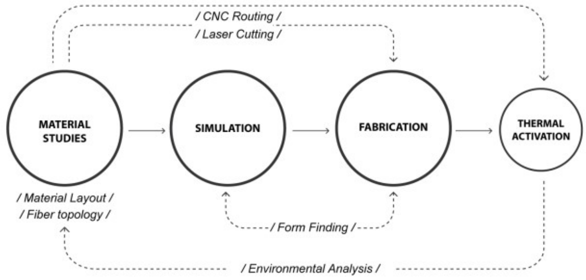

Figure 1: Design integrated workflow for development and testing of exergy-based responsive timber composites.

The research objective is pursued through a hybrid experimental method, integrating a set of prototypical and computational methods. Using oak veneer, the material studies are organized across three groups of material composites that are being activated, and tested, using a custom-made climate-controlled environmental chamber. The resulting bending behaviour of the responsive composites is being real-time tracked and implemented into a design-integrated high-resolution simulation framework. This, in return, allows for systematic comparative review of the composites' dynamic thermal responsive environmental and structural performance, in relation to operative temperature regulation, as well as evaluation and cross-validation against the prototypical material studies.

2.1 Prototyping studies

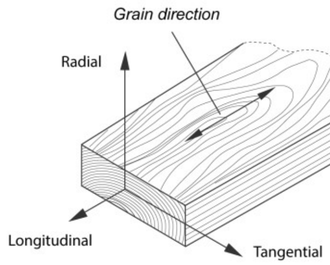

Figure 2: Wood anisotropy based on grain direction.

Due to its high thermal expansion coefficient tangentially to growth rings, wood transfers thermally activated dimensional changes into responsive bending behaviour [11]. The direction and magnitude of this responsive capacity is ingrained in the material's anisotropic characteristics, which are directly related to the anatomy of wood and specifically the fibre direction (fig.2). Employing a thermal environmental stimuli strategy, the selection of the right material is approached through research and understanding of the microstructural principles that facilitate the thermal actuation of wood. The enquiry employs a material survey across a large series of material layouts, configurations and compositions, where various wood types were tested in relation to their thermal responsive capacities. Quarter-cut oak veneer 0.6 mm was selected for its high thermal expansion coefficient [12] tangentially to growth rings (a_T =11, 9%), its high material strength (E=343 Nmm^2) and homogeneity of samples, presenting an almost linear grain topology. To maintain consistency among material experiments in relation to environmental stimulation, all material composites are being tested in a custom designed climate control environmental chamber. A thermal radiator of 1000 Watt, an ultrasonic humidifier, as well as relative and surface temperature and humidity control units provide a controlled climate conditioning. For the presented study, the conditions for activating the composites were programmed with the use of temperature and humidity sensors, as well as Arduino micro-controller. During all material experiments, a maximum of 38 °C Relative Temperature (RT) was reached, maintaining 30% Relative Humidity (RH). The climate-controlled setup allows the material composites to undergo several activation cycles under consistent conditions in relation to activation time, ensuring accuracy and high fidelity in the results.

2.1.1 Single-veneer elements

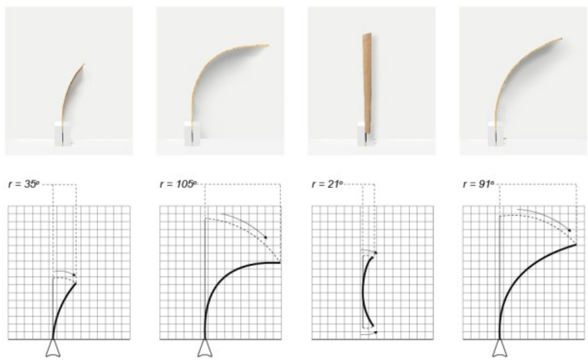

Figure 3: Principle curvatures of thermally actuated oak single veneer elements of varying dimensional ratio and grain directionality.

The experimental material studies use single veneer elements of 0.6 mm thickness and are based on variations in fibre directionality and material layout. In detail, the studies are organized across five fibre direction angles, 0^o, 30^o, 45^o, 60^o and 90^o and are combined with three material layouts, based on square, rectangular and triangular configurations. After being thermally stimulated, the material responds by dissipating the stress into an elastic deformation perpendicular to the fibre direction, expressed as bending (fig. 3). The synergy between fibre directionality and the element's dimensional considerations provides us with a great variety of responsive behaviours in terms of bending direction and magnitude.

2.1.2 Bi-layer composites

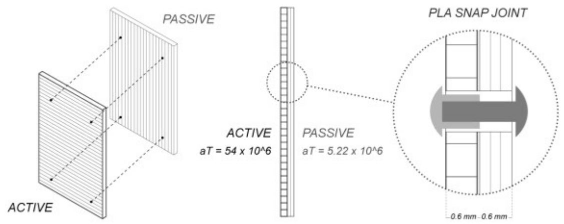

Figure 4: Structure of bi-layer veneer composites based on differentiated thermal expansion coefficient.

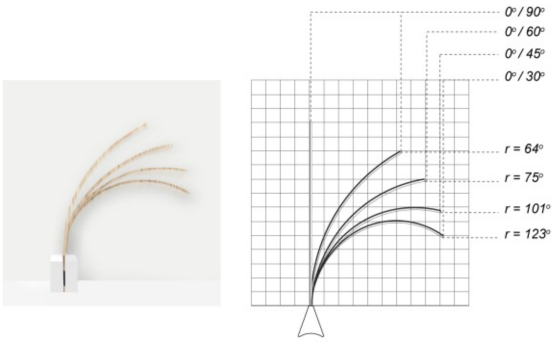

Figure 5: Principle curvatures of thermally actuated oak bi-layer composites of varying grain directionality.

Based on bilayer theory developed for thermally responsive bimetallic alloys, bi-layer composites describe the curvature resulting from combining multiple layers with different coefficients of expansion [13]. The bi-layer wood composite used for the research has been developed using two layers of oak veneer, one active and one restrictive, defined by their fibre direction (fig. 4).

The research employs veneer elements of opposing fibre directions-tangential and radial to growth rings, with high and low thermal expansion coefficient respectively. The resulting bi-layer composites allows for higher rigidity in larger responsive surfaces and functional variation in responsive curvature.

Moreover, there has been carried out extensive research [14] on different synthetic adhesives for thermal responsive composites, including acrylics, bonding materials and structural glues positioning the shear modulus as primary parameter for a suitable lamination. The material experiments show that alternative local binding methods such as sewing and snapping allow for fast assembly and disassembly, as well as eliminate the risk of delamination of the responsive composites after several activation cycles.

2.1.3 Functionally graded multi-grain composites

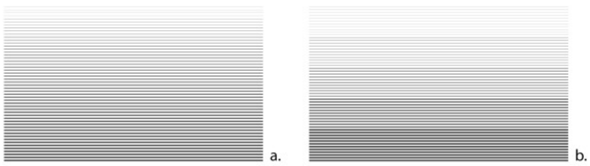

Figure 6: Composition of FGM through continuous (a) and stepwise gradation (b).

In a Functionally Graded Material (FGM) both the composition and the structure gradually change over the volume, resulting in corresponding changes in the properties of the material [15]. This is achieved when two different material ingredients change either gradually from one to the other (continuous gradation) or when this transition is performed in a discontinuous way (stepwise gradation) (fig. 6). The research employs a stepwise gradation process to form high-resolution wood composites, using gradual material layering deposition of various grain directionality oak veneer. This material distribution allows for local control of bending stiffness and direction (fig. 7). In the presented prototypical method, binding of the oak layers occurs in the form of local customized PLA snap joints, allowing for control of moving freedom between the elements as well as reuse of the same elements in other geometrical configurations (fig. 4).

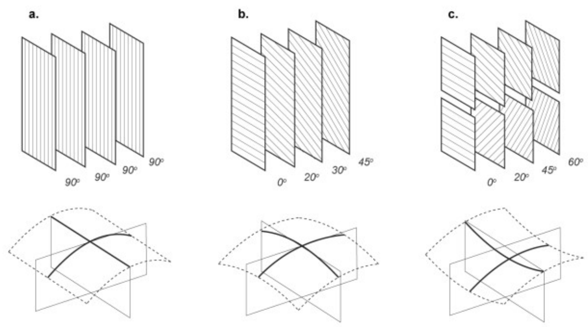

Figure 7: Various FGM configurations leading to monoclastic(a), synclastic(b) and anticlastic(c) curvatures.

2.2 Computational studies

Along with the material studies, the simulation, prediction and steering of the responsive behaviour and performance of exergy-based building composites incites research into the development of material-based computational methods and models. This give us a good insight into the possibility to reconceptualise the material use in architectural design, in order to fulfil formalized design requirements. However, programming a system's response in the material level requires an in-depth understanding of the characteristics of wood as a natural material. Moreover, it requires the development of material-driven computation strategies that incorporate a range of design, fabrication and actuation parameters [16]. While single-directional responsive curvature can be estimated mathematically through Geometric Representation Models (GRM) [12], the interaction between multiple layers can be a computationally intensive and complex task. For that reason the form-finding and overall structural behaviour of the responsive composites, in terms of deformation and bending stresses, is simulated with spring-based physics engine, using K2 solver in Grasshopper, Rhinoceros. In order to compute the differentiated behavioural response of all three groups of material composites based on environmental conditions, the research employs custom-made modules. This allows for implementation of the dynamics and critical influencing parameters for each material configuration. The form finding of the reactive elements occurs by assigning the grain orientation of each fibre into weighted values for hinges, along the internal edges of a triangulated mesh, corresponding to the material layout. The resulted vertex map of graded weighted values is being informed by the thickness and elastic limitations of the material. Moreover, it is recalibrated based on measurements from the physical experiments, with the use of infrared camera (Kinect V2) for real-time object tracking and point cloud export. The accuracy of the simulation at this level can be up or down sampled by changing the resolution of the mesh topology, eliminating the deviation between physical and digital tests, at the cost of higher processing time.

The described digital experiment represents a bottom-up approach, where the designer provides material specification data affecting the responsive performance and utilizes computational tools for simulating the emerging behaviour. In order to create a design-integrated workflow relating informed design iteration with material-driven fabrication strategies, the computational model was further developed, adopting a top down approach. Starting from a target principal curvature as input, a triangulated mesh is re constructed, carrying edges of the same spring strength. The target input curvature is then analysed and based on the resulting values coupled with the ratio between size and thickness of the desired material layout, the mesh edges are informed with differentiated strength values. After the geometry is simulated and unrolled using dynamic relaxation, the 2d pattern of the informed edges represent the grain topology. Thus, it can be used as fabrication file for the production of exergy-based wood composites with bespoke responsive capacities. This dual computational method allows for a synergy between design, performance and fabrication. Moreover, it proposes the emergence of a new design integrated workflow that not only entails high-resolution simulation of the system's ingrained material capacities, but also form a predictive modelling framework for producing material specification data from formalized design criteria.

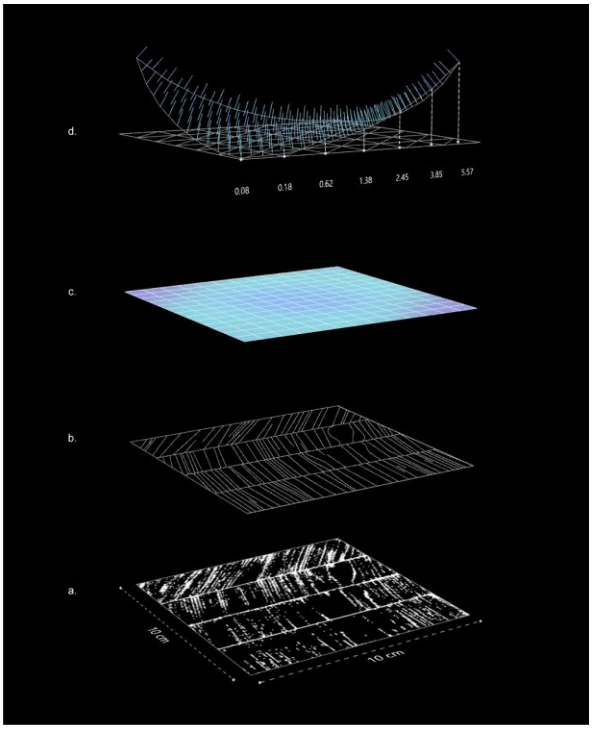

Figure 8: (a) Grain pattern bitmap, (b) Line detection, (c) Informed mesh topology, (d) Dynamic spring-based simulation displaying Gaussian curvature of activated FGM timber composite at 38 °C.

3. DESIGN EXPERIMENTATION

Through a series of design and material experimentation, this study attempts to analyse, manipulate and calibrate the hybrid bending behaviour of multi-directional oak veneer composites. Organized in a reciprocal open topology, the study discuss the development of a microclimate-sensitive responsive surface, which can be tuned to desired performance related to thermal sensation.

Through a physical demonstrator of 2 x 3 m, the study explores the thermal responsive behaviour of functionally graded multi-grain oak composites in relation to differentiated geometry, as part of an adaptive envelope demonstrator. Moreover, the enquiry presents the fabrication and assembly methods used for its development. Computational methods and computer-controlled fabrication machines enabled the design and production of the uncoated veneer structure. The specimen consists of 50 reactive multi-layer oak veneer elements of various grain directionality, leading to single, double and multi-directional bending. The system is developed around overlapping cells of 300 x 300 mm, using snap joints for binding the various oak veneer layers together, interlocked through CNC joints along their edges. The configuration ensures structural rigidity while minimizing weight. The dimensions of the elements used for the responsive composites were defined through an environmental benchmark model, created in Ladybug plugin for Grasshopper, Rhinoceros [17]. The model displays a parallel evaluation study of how the various bending states of the responsive membrane affect the amount of solar energy passing through the composite membrane, providing the designer with a direct relation between material behaviour and environmental performance. The experimental responsive specimen is being exposed and activated in 38°C RT, maintaining 30% RH. The responsive behaviour is expressed with variations in magnitude, ratio and bending direction and allows for local changes while addressing consistent global structural and environmental performance. Within these investigations, the hierarchy and the anisotropic characteristics of the composite is proved to be the driving force of the programmed deformation. With the use of infrared camera, the activated responsive material system is being real-time tracked and the resulted point cloud is used as validation method for the fidelity of the simulation. This allows for deviation analysis between the physical and digital studies. The system demonstrates the integration of a responsive material system into a functional, modular and highly adaptable system in an architectural scale.

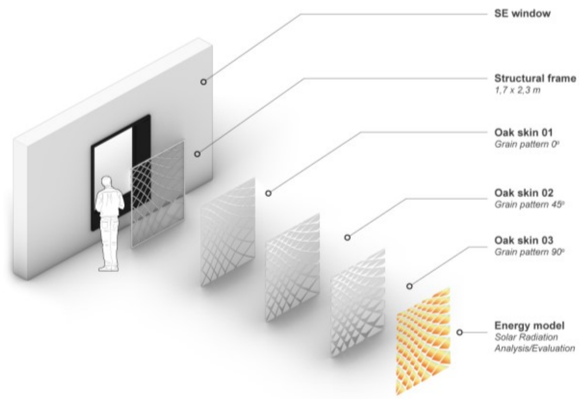

Figure 9: Thermal responsive functionally graded surface, using three multi-directional layers of oak veneer. The benchmark model ensures that the design system is tuned to desired performance related to thermal sensation.

4. RESULTS

The enquiry presents an experimental hybrid prototypical method employing advanced material studies and high-resolution simulation tools for exergy-based building composites. The study focuses on the development of adaptive material systems, developable into adaptive building envelopes. Through a material design survey across three groups of responsive timber composites - single veneer elements, bi-layers and FGM- and a computational framework for systematic comparative review of their dynamic thermal responsive and structural performance, the enquiry explores the potentials of a design-integrated workflow that allows for bidirectional exchange of information, between design and fabrication. Within this process, the role of the designer lies on the interfacing of those parallel simulation and design models, as well as the coordination of qualitative and quantitative data processing between the various resolution design agencies.

The case study proves that the integration of a hybrid material-driven adaptive workflow from design to production, can inform the design chain with a series of critical results, allowing for high precision performance steering of responsive systems:

1. The research findings suggest that fibre directionality constitute the main factor for steering the bending direction. The relation between size, shape and material thickness determines the bending magnitude as well as the reaction time needed for the responsive performance of the material composite. Thicker material samples require more time to address the temperature change into thermal material expansion and therefore will withstand the intrinsic deforming forces for a longer period. Moreover, in longer pieces that are cut across the grain direction, the resulting change in curvature is greater.

2. Homogeneity of samples. Even if oak is considered homogeneous wood type, it is still required a detection method of wood directionality for informing both the simulation and fabrication process and ensure consistent behaviour.

3. Single and bi-layer thermally activated veneer composites deliver single-directional curvature of various magnitude, while FGM multi-grain composites allow for multi-directional functional bending. These combine high resolution steering of performance with high material stiffness and thus, present an increased potential for implementation in building construction, as a responsive structural component. Moreover, the assembly strategy of tailoring responsive composites, combining multiple elements, overcomes the dimensional limitations of quarter-cut veneer (400-1200 mm in width) and allows for the production of increasingly larger systems.

4. Given the organic and extensive parameters of wood as a vascular tissue, the excessive or uneven distribution of heat due to UV radiation across the grain can cause uneven distribution of strain in the system. This may consequently result in microstructural damage (plastic deformation) and an overall reduction of responsiveness over time. This

increases material fatigue [10] and can affect the operational life of the system. Thus, it is a performative aspect that we cannot exclude from the simulation methods, used in the design process.

5. Material calibration is directly related to the environmental conditions and therefore, the same control that is being carried out through activation must be also maintained through fabrication process. Thus, it is required diligent measuring of the ingrained Moisture Content of wood, as well as control over relative temperature and humidity levels during production.

5. DISCUSSION

The case study is a limited enquiry and further work is needed to evaluate the performance of the exergy based building composites for the development of adaptive material systems across multiple samples and scales with different strategies of differentiation. The development of a responsive architectural system based on anisotropic material properties of wood, presents methodological and technical challenges that need to be considered and further implemented, within the design chain. Thus, the emergence of new design integrated workflows that not only entail high-resolution simulation of the material behaviour and performance, but also form a predictive modelling framework of the system's behavioural shifts and inconsistencies, after several operational cycles, becomes crucial.

Further exploration needs to occur for the development of adopted and adapted design methods that can interface various resolution data between the prototypical material studies, the computational model and the fabrication process. This will allow for high-resolution steering of the system's thermal responsive and environmental performance. This careful classification of data exchange will also allow for applying the presented methods in a bigger architectural scale, maintaining accuracy.

Moreover, the possibility of employing robotic fabrication for the development of the responsive material composites could allow for high-resolution material specification that can address design and performance demands, with a build-per requirement approach. This in return could increase the product's structural and environmental performance, enhance material efficiency, promote material economy and optimize material distribution, enabling the implementation of a bespoke material-driven fabrication into design, as an aspect of sustainability. Finally, along with the various grain material deposition that is being investigated in the presented study, the shift towards a multi-material layering could introduce new hybrid properties in the responsive architectural system.

REFERENCES

1. Kretzer, M.: Information Materials, Smart Materials for Adaptive Architecture. Springer (2016).
2. Government UK. Strategy for sustainable construction (2008).
3. IPCC. Summary for policymakers. Climate chage 2014 Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects (2014).
4. Kolarevic, B., Parlac, V.: Adaptive, Responsive Building Skins. In: Building Dynamics: Exploring Architecture of Change. pp. 69-88. Routledge (2015).
5. Shukuya, M.: Exergy concept and its application to the built environment. In: Building and Environment, 44, pp. 1545-1550 (2009).
6. Holstov, A., Farmer, G., & Bridgens, B.: Sustainable materialization of responsive architecture. Sustainability, 9(3) (2017).
7. Wood, D., Vailati, C., Menges, A., & Rüggeberg, M.: Hygroscopically actuated wood elements for weather responsive and self-forming building parts – Facilitating upscaling and complex shape changes. Construction and Building Materials, 165, pp. 782–791 (2018).
8. Worre Foged, I., & Pasold, A.: Thermal Activated Envelope, Development of a Method and Model for Programming Material Behaviour in a Responsive Envelope. In Proceedings of the 33rd eCAADe Conference - Volume 2, Vienna University of Technology, Vienna, Austria, pp. 449–458 (2015).
9. Fragkia, V. & Worre Foged, I.: Methods for the Prediction and Specification of Functionally Graded Multi-Grain Responsive Timber Composites. In Proceedings of the 38th eCAADe Conference, TU Berlin, Berlin, Germany (2020).
10. Vazquez, E., Randall, C., Duarte, J.P.: Shape-changing Architectural Skins, A Review on Materials, Design and Fabrication Strategies and Performance Analysis. In Journal of Façade Design & Engineering, 7(2), pp. 93-114 (2019).
11. Record, S.J.: Mechanical properties of wood, Gutenberg (1999).
12. Foged, I., Pasold, A.: An oak composite thermal dynamic envelope. In: Structures and Architecture - Proceedings of the 3rd International Conference on Structures and Architecture, ICSA (2016).
13. Timoshenko, S.: Analysis of Bi-Metal Thermostats, J Opt Soc Am, 11(3), pp.233-255, (1925).
14. Foged, I.W, Pasold, A and Pelosini, T.: Material Studies for Thermal Responsive Composite Envelopes. In Proceedings of eCAADe 2019, Porto, p. 207–214, (2019).
15. Miyamoto, Y, Kaysser, W.A, Rabin, B.H, Kawasaki, A and Ford, R.G.: Functionally Graded Materials. Design, Processing and Applications, Springer (1999).
16. Wood, D., Correa, D., Krieg, O., Menges, A.: Material computation-4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces. International Journal of Architectural Computing, Vol. 14(1) 49–62 (2016).
17. Roudsari, M.S., Pak, M., Smith, A. and Gordon Gill Architecture. Ladybug: A Parametric Environmental plugin for Grasshopper to help Designers create an environmentally conscious design. Proceedings in Conference of International Building Performance Simulation Association (2013).